1930s: Zwicky proposed **Dark Matter** to explain the mass to light ratio of Coma galaxy cluster.
Model Independent Limit on DM Annihilation Cross Section

- Assume DM annihilations only produce Standard Model final states.

- Stringent upper limit on total annihilation cross section can be obtained by assuming only neutrinos are produced in final states (worst case, least visible).

\[
\chi \rightarrow \text{All Standard Model final states} = \text{"Visible" states: } \gamma\gamma, q\bar{q}, e^+e^-, \ldots + \text{"Invisible" states: } \bar{\nu}\nu
\]

- Anything else will eventually produce much more visible gamma rays (leading to a stronger limit).
Compare to Atmospheric Nu Flux

“Even Neutrinos are overproduced”

Yuksel, Horiuchi, Beacom, Ando 2007
Beacom, Bell, Mack 2006
Constraints on sterile neutrino DM

Constraints derived from various experiments:

- Yuksel, Beacom, Watson 2008
- Teegarden, Watanabe 2006
- Kishimoto, Fuller 2008
- Abazajian, Fuller 2002

Graphical representation of constraints on sterile neutrino mass $m_s$ and mixing angle $\sin^2 \theta$.
DM and Multi-GeV Positron Excess
TeV Gamma Rays From Geminga and Multi-GeV Positron Excess

Hasan Yüksel
Bartol Research Institute & University of Delaware

KICP Workshop
The impact of high-energy astrophysics experiments on cosmological physics

27-28 October, 2008

(in collab. with Matt Kistler and Todor Stanev)
Geminga:

- Radio quite
- First pulsar to be discovered through gamma rays
- Until recently, no evidence of a high energy activity beyond immediate neighborhood

\[ r_G \sim 250^{+120}_{-62} \text{ pc} \]
\[ t_G \sim 3 \times 10^5 \text{ yr} \]
# Milagro Galactic Plane Survey

<table>
<thead>
<tr>
<th>Object</th>
<th>Location $(l, b)$</th>
<th>Flux$^c$ at 20 TeV $\times 10^{-15}$ TeV$^{-1}$cm$^{-2}$s$^{-1}$</th>
<th>Extent Diameter (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crab</td>
<td>184.5, -5.7</td>
<td>10.9 $\pm$ 1.2</td>
<td>-</td>
</tr>
<tr>
<td>MGRO J2019+37</td>
<td>75.0, 0.2</td>
<td>8.7 $\pm$ 1.4</td>
<td>$1.1^\circ \pm 0.5^\circ$</td>
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<tr>
<td>MGRO J1908+06</td>
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<td>8.8 $\pm$ 2.4</td>
<td>$&lt; 2.6^\circ (90% CL)$</td>
</tr>
<tr>
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<td>9.8 $\pm$ 2.9</td>
<td>$3.0^\circ \pm 0.9^\circ$</td>
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<tr>
<td>C1</td>
<td>77.5, -3.9</td>
<td>3.1 $\pm$ 0.6</td>
<td>$&lt; 2.0^\circ (90% CL)$</td>
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<tr>
<td>C2</td>
<td>76.1, -1.7</td>
<td>3.4 $\pm$ 0.8</td>
<td>-</td>
</tr>
<tr>
<td>C3</td>
<td><strong>195.7, 4.1</strong></td>
<td><strong>6.9 $\pm$ 1.6</strong></td>
<td><strong>2.8^\circ \pm 0.8^\circ</strong></td>
</tr>
<tr>
<td>C4</td>
<td>105.8, 2.0</td>
<td>4.0 $\pm$ 1.3</td>
<td>$3.4^\circ \pm 1.7^\circ$</td>
</tr>
</tbody>
</table>
Immediate Implications:

• Milagro detection puts Geminga among growing class of TeV PWNe

• Detection of TeV gamma rays indicates the existence of a nearby cosmic ray accelerator:
  – If gamma rays have a leptonic origin, the source is young & close enough to make a plausible contribution to CR positrons
  – Alternatively, a neutrino signal would be expected from a hadronic source
More Distant PWN by HESS

HESS J1825-137, Aharonian et al.
TeV Gamma Rays from Geminga

\[
d\frac{N_d}{d\gamma} = N_0 \gamma^{-\alpha} e^{-\gamma/\gamma_{max}} \quad \gamma_{max} = \frac{E_{max}}{m_e c^2}
\]

\[
\frac{d\Phi}{dE_{\gamma}} = \frac{c}{4\pi r^2_G} \int d\gamma \int dE_{ph} \frac{dN}{d\gamma} n_{ph}(E_{ph}) \sigma_{KN}(\gamma, E_{ph}, E_{\gamma})
\]

\[\alpha = 2, \quad E_{max} = 500 \text{ TeV}\]

\[\mathcal{E}_e (\gtrsim 1 \text{ GeV}) \approx 10^{45}\]
Galactic Plane by EGRET

Fig. 2g: 500-1000 MeV

Fig. 2h: 1000-2000 MeV

Fig. 2i: 2000-4000 MeV

Fig. 2j: 4000-10000 MeV
Fermi (GLAST) / Veritas Prospects
Positron Injection to ISM & Diffusion

\[
\frac{\partial n}{\partial t} = \frac{D(\gamma)}{r^2} \frac{\partial}{\partial r} r^2 \frac{\partial n}{\partial r} + \frac{\partial}{\partial \gamma} [\ell(\gamma) n] + Q(\gamma)
\]

\[
D(\gamma) = D_0 (1 + \gamma/\gamma_*)^\delta
\]

\[
\ell(\gamma) = \ell_0 \gamma^2
\]

\[
Q(\gamma) = \frac{dN}{d\gamma} \delta(r) \delta(t - t_G)
\]

\[
D_0 \approx 4 \times 10^{27} \text{ cm}^2\text{s}^{-1}
\]

\[
\gamma_* \approx 6 \times 10^3, \delta \approx 0.6
\]

\[
\ell_0 \approx 5 \times 10^{-20} \text{ s}^{-1}
\]

\[
n(r, t, \gamma) = \frac{dN/d\gamma}{\pi^{3/2} r^3} (r/r_d(t, \gamma))^3 e^{-(r/r_d(t, \gamma))^2} \frac{(1 - \ell_0 t \gamma)^{2-\alpha}}{(1 - \gamma/\gamma_c)^{1-\delta} / [(1 - \delta) \gamma/\gamma_c]}^{1/2}
\]

\[
r_d(t, \gamma) \approx 2 \left( D(\gamma) [1 - (1 - \gamma/\gamma_c)^{1-\delta}] / [(1 - \delta) \gamma/\gamma_c] \right)^{1/2}
\]

\[
E = 2 (10, 50) \text{ GeV} \quad r_d \approx 150 (200, 300) \text{ pc}
\]

Atoyan, Aharonian, Volk, 1995
Local Positrons from a Nearby Continuously Emitting Source

\[ n_\odot(\gamma) = \int^{t_G} dt \, n(r_G, t, \gamma) \quad d\dot{N}/d\gamma = \dot{N}_0 \gamma^{-\alpha} e^{-\gamma/\gamma_{max}} \]

\[ \dot{N}_0 = \mathcal{L}_e(t) \left( m_e c^2 \int_{\gamma_{min}} \gamma^{-\alpha+1} e^{-\gamma/\gamma_{max}} d\gamma \right) \]

Assuming breaking via magnetic dipole radiation:
Pulsar spin down luminosity evolves as

\[ \propto (1 + t/t_0)^{-\frac{n+1}{n-1}} \]

The injection rate of relativistic e-e+ by Geminga:

\[ \mathcal{L}_e(t) = \frac{\mathcal{E}_G}{t_G} \frac{(1 + (t_G - t)/t_0)^{-2}}{\int^{t_G} dt' (1 + (t_G - t')/t_0)^{-2}} \]

Geminga was much stronger in the past and dominated the TeV sky: Multi-GeV positrons may still be reaching us today.
Background Cosmic Ray Fluxes & Plausible Geminga Contributions

\[ t_G = 3(3,2) \times 10^5 \text{ yr} \quad \mathcal{E}_G \approx 2(5,2) \times 10^{48} \text{ erg} \quad r_G = 2(3,2) \times 10^2 \text{ pc} \]
Accounting for Positron Excess?

Yuksel, Kistler, Stanev 2008

PAMELA should yield an improved picture of the positron fraction
Hadronic Alternative: TeV Neutrinos

- If a nucleonic wind carry away much of the spin down energy of pulsar, gamma rays may be produced via decay of neutral pions from hadronic scattering
- $\Rightarrow >1$ Neutrino-induced muon in IceCube

![Graph showing Neutrino flux and muon production](image_url)
Amanda-II Hot(test) Spot

<table>
<thead>
<tr>
<th>Candidate</th>
<th>$\delta(^\circ)$</th>
<th>$\alpha(h)$</th>
<th>$\Phi_{90}$</th>
<th>$p$</th>
<th>$\Psi(^\circ)$</th>
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<td>3C 273</td>
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<td>1.6</td>
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<td>LS I +61 303</td>
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<td>6.76</td>
<td>0.44</td>
<td>1.5</td>
</tr>
</tbody>
</table>
Conclusions

• More data should become available soon:
  – **GeV Gamma Rays**: Fermi (GLAST)
  – **TeV Gamma Rays**: Veritas, Future ACTs
  – **Multi-GeV Positrons**: PAMELA, AMS?
  – **TeV Neutrinos**: IceCube

• Which may result in:
  – Developing more detailed models, including time & spatial evolution in the source
  – Unraveling Multi-GeV positron excess?
  – Discovering First TeV neutrinos source?